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Project Report
FCT-5

Large Aperture Multi-dimensional Laser Radar Testbed

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Hugh L. Southall

Hugh L. Southall, Lt. Col., USAF
Chief, ESD Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

LARGE APERTURE MULTI-DIMENSIONAL LASER RADAR TESTBED

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LEXINGTON MASSACHUSETTS

ABSTRACT

A 39 cm aperture multi-dimensional laser radar has been built and made operational. This sensor acquires pixel registered range, Doppler, 3-5μm passive, and visible passive data. Range is digitized at 200 MHz for .75m range resolution, Doppler is resolved to .5 mph with a SAW spectrum analyzer. Multi-dimensional images can be taken with an angular resolution of from 33μrad to 1mrad. Image size and data flow are controlled by a minicomputer. The technical details of this laser radar testbed are the subject of this report.

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1.0 INTRODUCTION

A large aperture (39 cm) multi-dimensional laser radar has been built and operated since the spring of 1987. The open design philosophy of this radar lends itself well to laser radar technology advancement. The radar employs a pulse-tone waveform for essentially simultaneous unambiguous range and Doppler measurements of the target which is resolved to 33μrad.

The range is measured absolutely to 75cm over the design ambiguity of 7 km. Since the radar uses peak detection logic this corresponds to a digitization rate of 200 MHz. This high rate of continuous analog-to-digital conversion is achieved by using two 100 MHz digitizers running in phase quadrature.

The Doppler Channel is processed with a SAW spectrum analyzer. This technology was developed at Lincoln Laboratory and has been reported on in detail elsewhere.[1] There are two interchangeable SAW devices with a half and a third mile per hour resolution.

Two bore-sighted passive detectors are also incorporated in the system: a visible CCD television in place before the scanners, and a single 3-5μm InSb detector after the scanners. The InSb detector has a temperature resolution of .7°C. It was incorporated to facilitate tracking of a hot object.

The telescope has a full 39 cm clear aperture and uses an off-axis parabola, hyperbolic secondary, and spherical tertiary. It is a focused system using all reflective optics, and is diffraction limited in the IR and twice diffraction limited in the visible. The telescope incorporates a 'pop-up' relay optic which effectively reduces the aperture to 13 cm which is comparable with other Lincoln Laboratory Laser Radars. The technical specifications of each of the sub-assemblies are given in the following chapters.

Section 2.0 contains a description of the system hardware including the Optical design, waveform generation, and the detection and recording electronics. Special purpose hardware was constructed to perform the peak detection in the range and Doppler channels.

In Section 3.0, we report on the computer control of the system. A Perkin Elmer 3210 minicomputer was selected to handle the system control because of its dual bus structure. The large data bandwidth is handled on the internal Direct Memory Address bus (DMA), while its separate lower bandwidth control (MUX) bus performs device servicing. Computer communication is handled through a programmable touch screen and/or terminal. The computer also handles the system clock, scanners, pulser, and digitizers. Data is recorded in real time on a 6250 bpi tape drive.

1.1 System Specification

A. Optics

Aperture	39 cm	13 cm
Magnification	48 x	16 x
Field of View	2x4 mrad	6x12 mrad

Focused system

Scanning in intermediate image planes

B. Lasers

25 W CW CO_2 grating tuned (P20 operation)

1 W cavity dumped waveguide CO_2 32 ns pulse width

Pulse-Tone waveform: 32 ns pulse + 50 μs tone

C. Electronics

IF sensitivity approx -125 dbm

Range digitizer 8 bit intensity

Absolute range 11 bits (75cm resolution)

Doppler 8 bit frequency in 10 MHz bandwidth

Peak detection in range and Doppler

Passive digitizer 12 bit intensity

3210 Perkin Elmer minicomputer controlled

Pixel rate aprox. 20 kHz

Frame size fully programmable

2.0 HARDWARE DESCRIPTION

This section contains a description of the large aperture testbed laser radar optics, pulse-tone generation, IF train, and range, Doppler, and passive processors. Figure 1 is an overall system block diagram indicating the various subassemblies. Greater detail of each subassembly is given in the following sections.

2.1 Telescope

The telescope consists of a large off-axis parabola, hyperbolic secondary, and spherical tertiary which produce 24x magnification at the vertical scanning galvanometer. An additional 2x magnification is provided by two spherical relay mirrors to obtain 48x magnification at the small horizontal scanning galvanometer. A flip-up relay mirror combined with a change in the amplitude and bias of the vertical scan produce a 2/3x relay for a total of 16x magnification with a larger field of view. All of the spherical mirrors are tilted and decentered to provide clearance. Some of them also have to be truncated. The basic telescope specifications have been given in the introduction.

The RMS wavefront error at 10.6 microns averages .005 waves at 48x magnification and .008 waves at 16x. These small RMS numbers imply performance which is diffraction limited in the infrared and near diffraction limited in the visible. Due to the all reflective nature of the design, there are no color aberrations. The pupil wander on the primary is ± 3 mm for 48x and ± 16 mm for 16x. Table 1 lists the nominal locations of the telescope optics relative to the secondary.

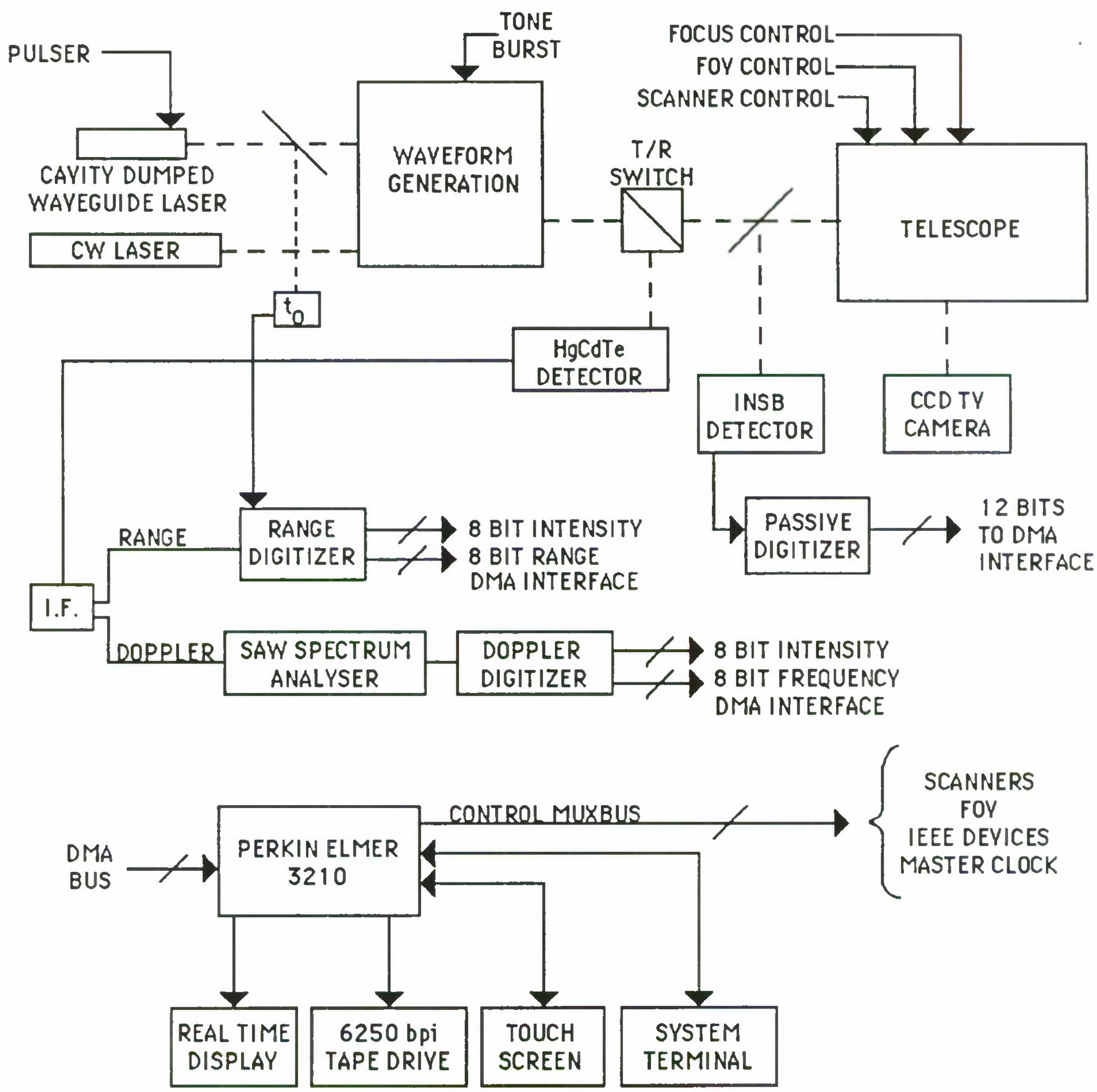

FIGURE 1. BLOCK DIAGRAM OF THE MULTI-DIMENSIONAL LASER RADAR TESTBED.

Table 1

Nominal Telescope Layout

Mirror	Location*		Tilt	Clear Aperture*	
	Y	Z	Degrees	X	Y
Primary	304.8	2276.78	3.434 down	393.7	
Secondary	0.	0.	0.	107.	
Tertiary	-12.69	2024.73	1.389 down	236.	122.
Galvo 1 48x	-68.64	1224.6	1.50 down	17.	
Galvo 1 16x	"	"	6.439 down	5.7	
Relay 1 48x	-140.69	1811.33	4.5 up	160.	17.
Relay 1 16x	-126.90	1416.60	9.439 up	64.	6.
Relay 2	-109.43	916.16	4.5 down	147.	9.
Galvo 2	-146.12	1215.02	7.0 up	8.4	

The large galvo is dichroic, passing visible radiation which is detected via 1-1 relay optics by a CCD television camera. The dichroic reflects greater than 98% for wavelengths beyond 1μm. The small horizontal galvo scanner is totally reflective. A second dichroic is placed in the optical path

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*Units are in mm. The right-hand coordinate system has its origin at the center of the secondary with +y up and the optics axis is along z.

before the input to the telescope which splits off 3-5μm radiation for detection by the InSb detector. It is 82% reflective in the 3-5μm band and 98% transmissive at 10.6μm.

The transmit/receive switch consists of a Brewster window/quarter wave plate polarization switch. Vertical polarization is transmitted (up to the $\lambda/4$ plate) and horizontal polarization is received at the detector.

The detector is a commercial (New England Research Center, Inc. #MPV11-.15-BD60) cooled (liquid nitrogen) HgCdTe photovoltaic with a matched 150 MHz preamplifier/bias tee. The detector has an active area of 1.0E-4 cm^2, quantum efficiency of 84%, responsivity (10.6μm) of 6.8 A/W, and an impedance of 2.57 kΩ.

The indium antimonide 3-5μm detector is operated as a photovoltaic. The active area is 75x75μm, responsivity is 3. A/W, impedance is >5 MΩ, and its detectivity is 3.0×10^{11} cm-$\sqrt{Hz}$, the bandwidth is DC to 40kHz.

2.2 Waveform Generation

A pulse-tone waveform is used for near simultaneous range Doppler measurements.[2] Figure 2 is a schematic of the pulse waveform generation scheme. Two acoustooptic modulators are used. AO_1 provides the local oscillator beam for heterodyne detection which is frequency shifted by 80 MHz from the CW beam. AO_2 is the beam multiplexer and runs at 40 MHz. When AO_2 is on, the CW Doppler tone is shifted by 40 MHz and transmitted. The

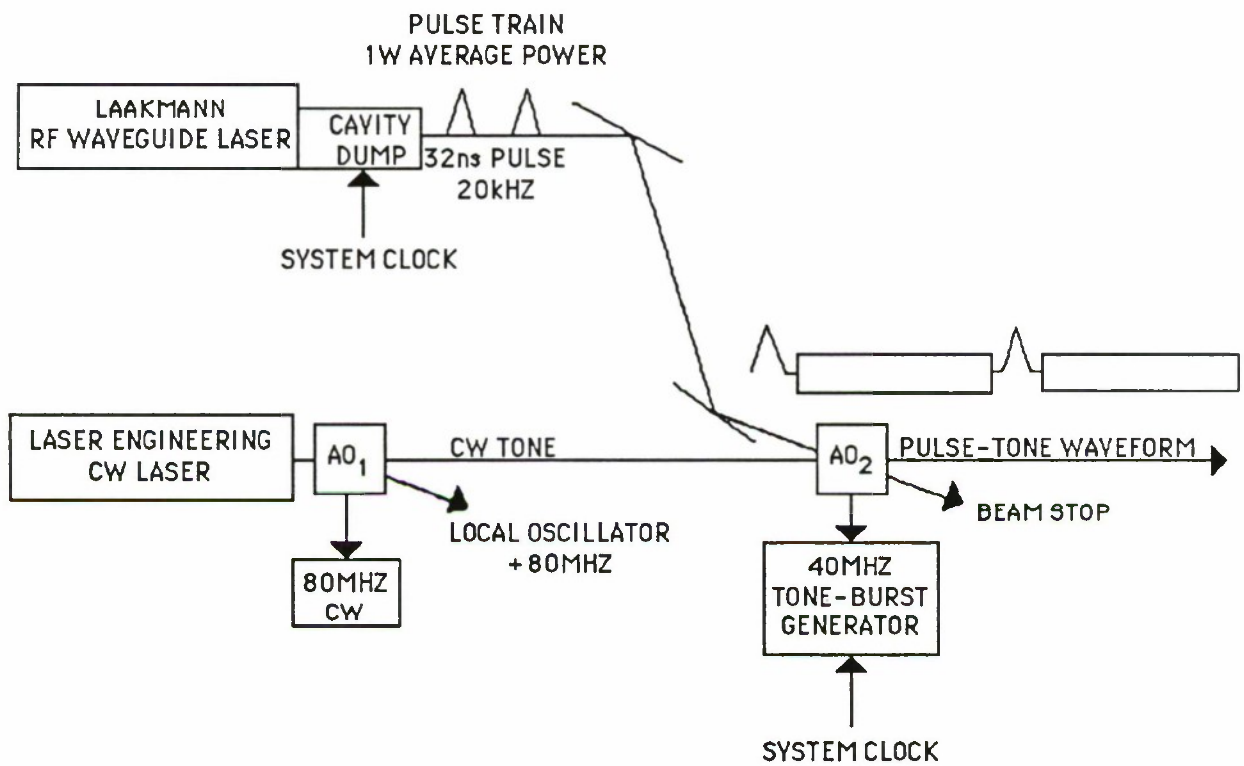

FIGURE 2. PULSE-TONE WAVEFORM GENERATION SCHEMATIC; GENERATES A 32NS PULSE FOLLOWED BY A 30us TO 50us CW TONE.

turn on/off time of AO_1 is about .5μs. Thus in the Doppler channel, the intermediate frequency (IF) occurs at 40MHz. Since the local oscillator is higher in frequency (at 80 MHz), Doppler shifts from targets moving away result in up-shifted frequencies (greater than 40 MHz) and vice versa.

When AO_2 is off the pulsed laser is coupled into the optics transmit path. If the pulsed laser operates at the same frequency as the CW laser the pulse IF occurs at 80 MHz. By adjusting the frequency difference between the two lasers one has a certain freedom in selecting the pulse IF. Generally the system is run so that the pulse IF is centered at 60 MHz with a 20 MHz bandwidth.

The time multiplexer AO_2 is controlled with an HP 8116A waveform generator operating in the tone burst mode triggered by the system clock. It has an IEEE488 interface and can be driven by the system computer.

2.3 Intermediate Frequency (IF) Chain

Heterodyne detection is used to obtain shot noise limited performance. Proper care is taken to ensure that the shot noise dominates all other system noise. Figure 3 is a schematic of the IF amplifier chain. The preamp is a matched amplifier bias network and provides 30 db gain. The signal is then split into two channels for separate pulse and Doppler processing. The pulse channel includes a time domain filter which consists of a

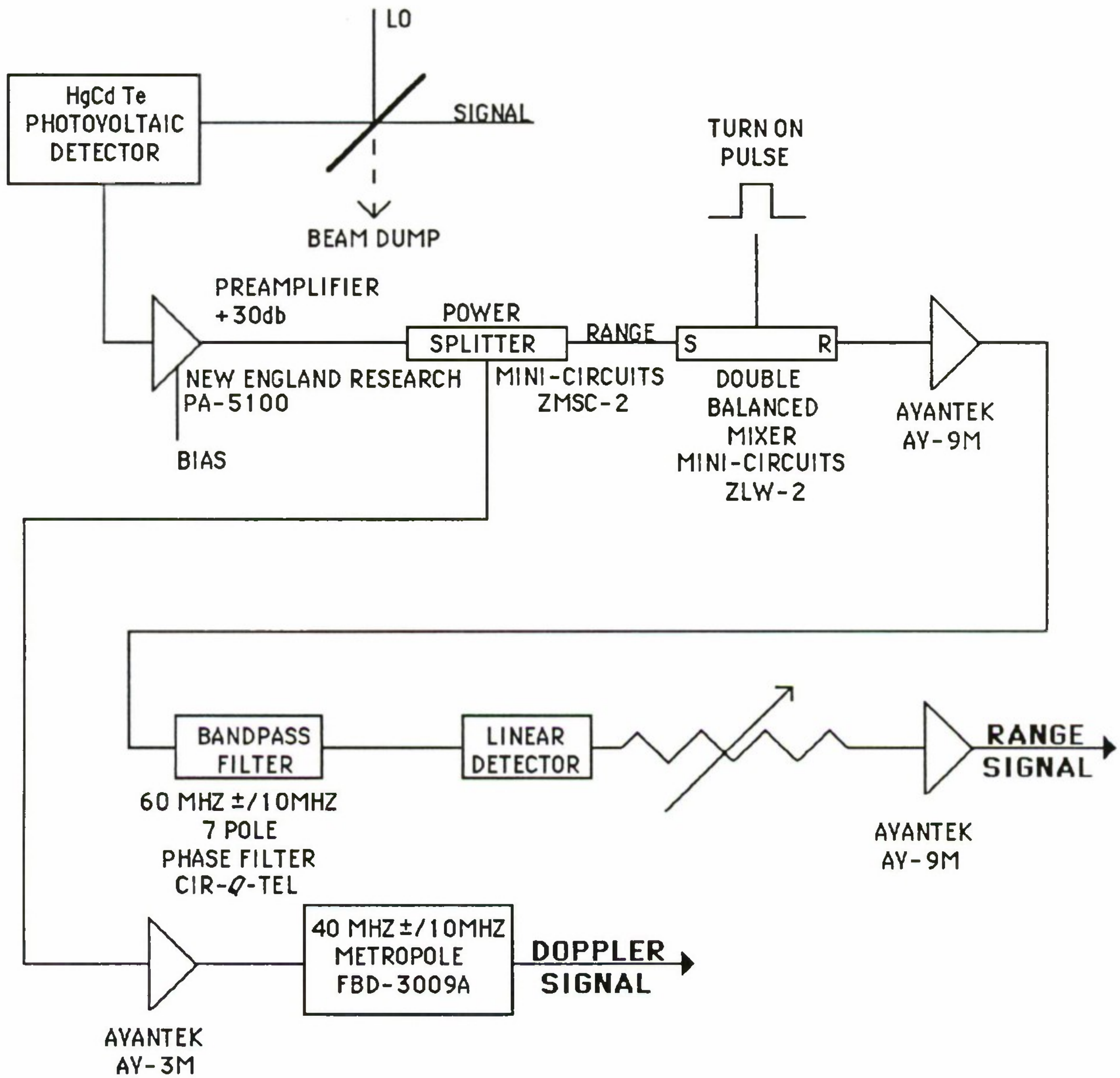

FIGURE 3. SCHEMATIC FOR THE INTERMEDIATE FREQUENCY RADIO FREQUENCY CHAIN.

fast RF switch (Mini-Circuit double balanced mixer model ZLW-2-1W), the purpose of which is to prevent saturation of subsequent stages of amplification during the transmission of the pulse. Since the system is monostatic, narcissus can cause saturation of the IF electronics. Time domain filters are essential for short range ($\leq$ 1km) operation. IF filters and attenuation pads are placed to select channel gain and bandwidth.

2.4 Range Digitizer

The range channel takes two signals, the IF from the HgCdTe detector, and a second signal from a room temperature HgCdTe which detects the laser pulse and provides the t_0 timing pulse for range. The IF signal is linearly detected. Figure 4 is a schematic of a linear detection network used in the pulse and Doppler processing. The lowpass filter determines the bandwidth of the pulse analog channel and is typically 13 MHz. The t_0 signal is passed through a constant fraction discrimination circuit (CFD-584 EG&G Ortec NIM module) which results in a NIM pulse that triggers the range clock. The pulse cavity dump clock is provided by the system clock and is generated by the system computer.

Range is determined by peak detection logic. A specially designed analog to digital converter is clocked at 200 MHz. The output of the A-to-D is passed through a comparator, the

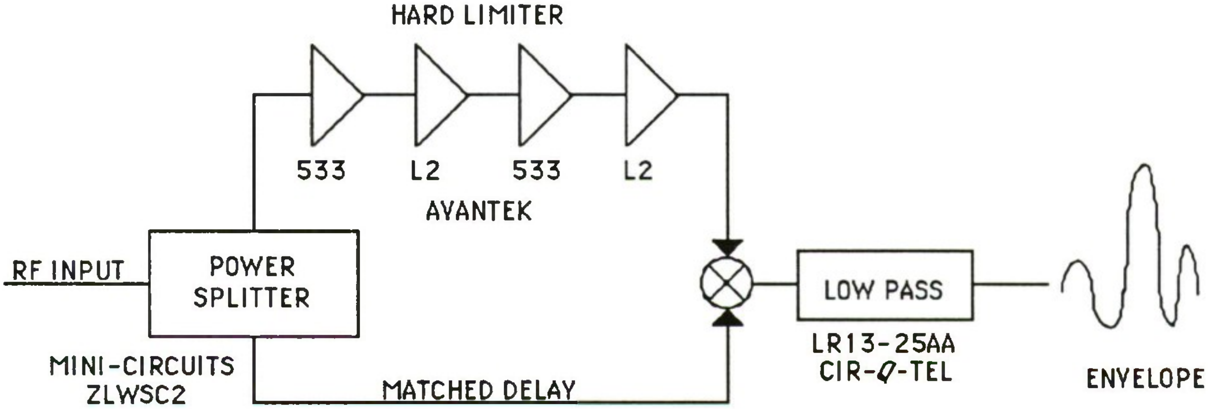

FIGURE 4. SCHEMATIC FOR THE RANGE AND DOPPLER CHANNEL LINEAR DETECTOR.

largest amplitude value in the range gate is selected along with the time that it occurred. Thus range and range intensity are output. The range gate is 11 bits wide and the gate start is recorded in the header information.

The 200 MHz A-to-D consist of two 100 MHz A-to-D's run in phase quadrature. At these high speeds 100KECL logic is used with ground plane and twisted pair construction techniques. Figure 5 is a block diagram of the range digitizer. The peak detection circuit consists of a comparator. Each A/D output is compared with the previously stored largest value. The largest value is selected along with the time (corresponding to range) it occurred.

2.5 Doppler Digitizer

The analog Doppler channel is 10 MHz wide centered at the 40MHz Doppler IF. This signal is input to a Surface Acoustic Wave device (SAW) spectrum analyzer. Figure 6 is a schematic of the SAW spectrum analyzer. It consists of 3 key components, a RF impulse generator, a SAW expander, and a SAW compressor. The impulse generator makes 4 cycles of a 125 MHz signal which is input to the SAW expander. The output of the expander is a down-chirp from 140 MHz to 110 MHz at 1 MHz/μs. The chirp is amplified and mixed with the Doppler signal. The output of the mixer is input to the SAW compressor which generates a pulse (pulses) whose output time is proportional to the Doppler

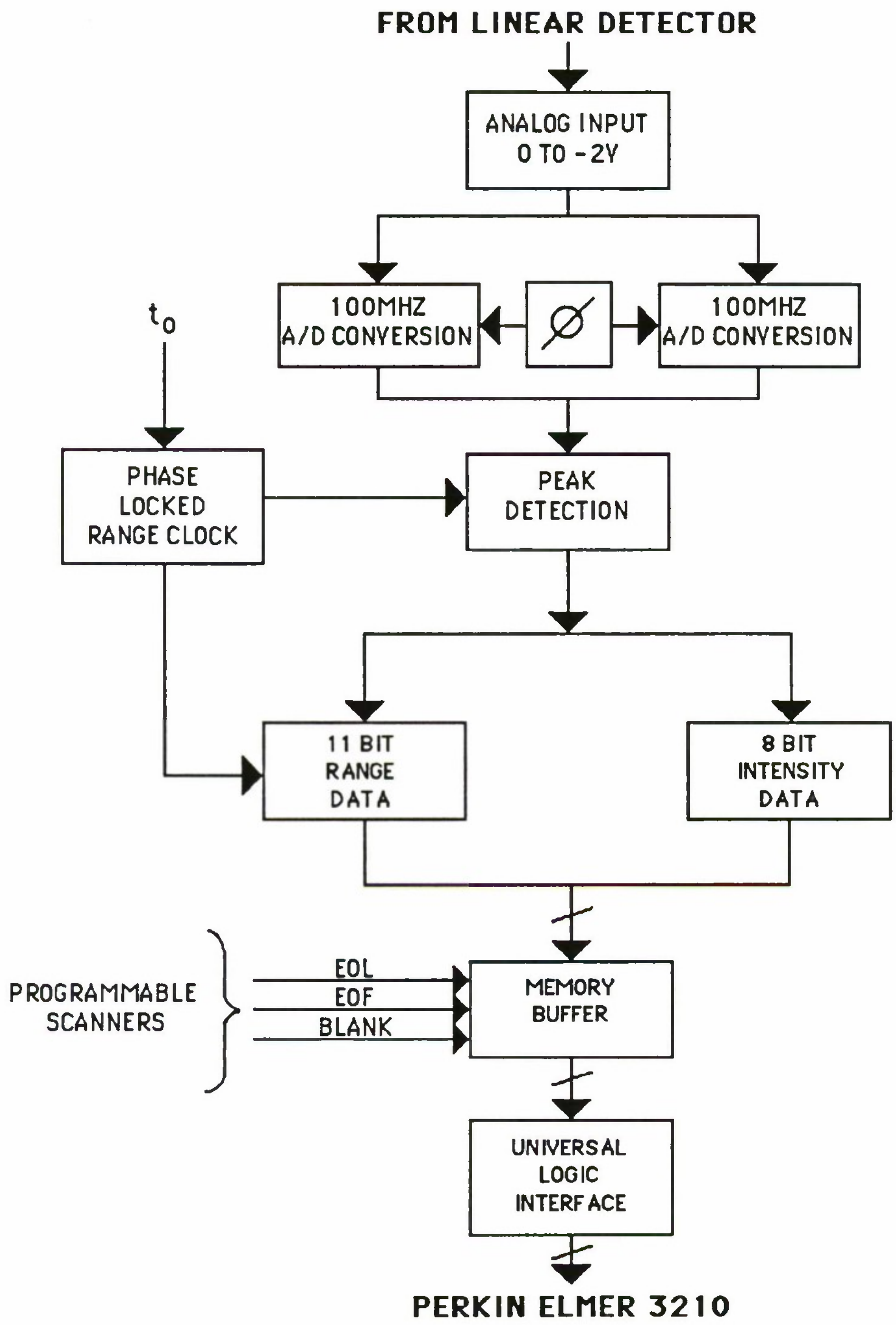

FIGURE 5. BLOCK DIAGRAM FOR THE 200 MHz RANGE DIGITIZER PROVIDING 8 BITS OF RANGE INTENSITY AND 11 BITS (75cm) OF RANGE.

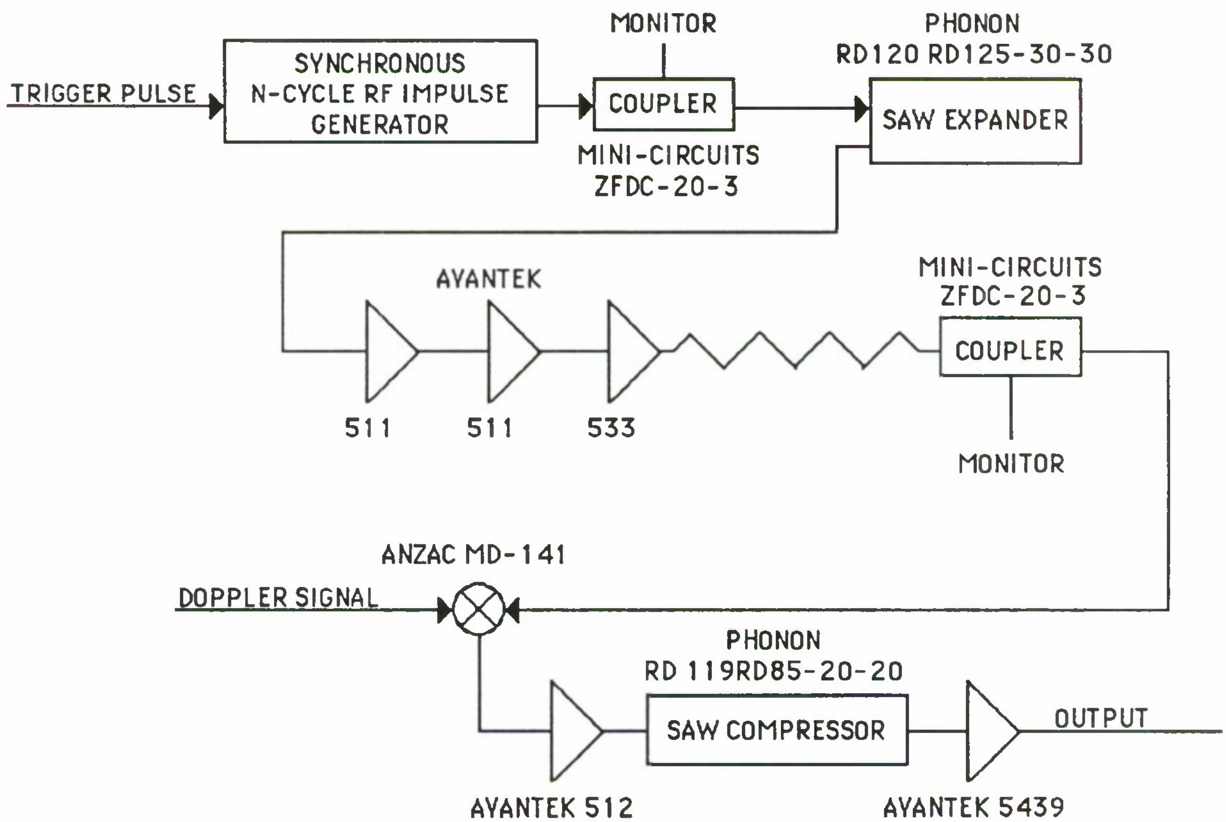

FIGURE 6. SURFACE ACOUSTIC WAVE (SAW) SPECTRUM ANALYZER PROVIDING 50kHz RESOLUTION OVER 10 MHz BANDWIDTH.

frequency. The SAW compressor has 30db of sidelobe weighting and 70 db of dynamic range (voltage) with a maximum PRF of 25 kHz determined by compression time and signal bandwidth.

The pulse output of the SAW is linearly detected as with the range channel. The pulse is input to a peak detection circuit with 8 bits of pulse position (frequency) and amplitude resolution. Figure 7 is a block diagram of the Doppler channel digitizer together with the pulse detection circuitry. The Doppler digitizer uses conventional technology and construction techniques.

2.6 Passive Channel

The 3-5μm passive channel is digitized with a 14 bit analog to digital converter running from the system clock (pixel rate of 20kHz nominal). The A-to-D and computer interface use conventional pass-on-logic (simple memory buffer) which implies a 50μs pixel dwell time.

2.7 Touch Screen

A Lexidata 3452-3-LP monitor together with a Mitsubishi C6912 touch screen provide a programmable control screen for system operation. Figures 8-9 show the main touch screen and sub screens. All control settings available from the touch screen are backed up through the system keyboard. Further explanation of touch screen functions are found in the next section.

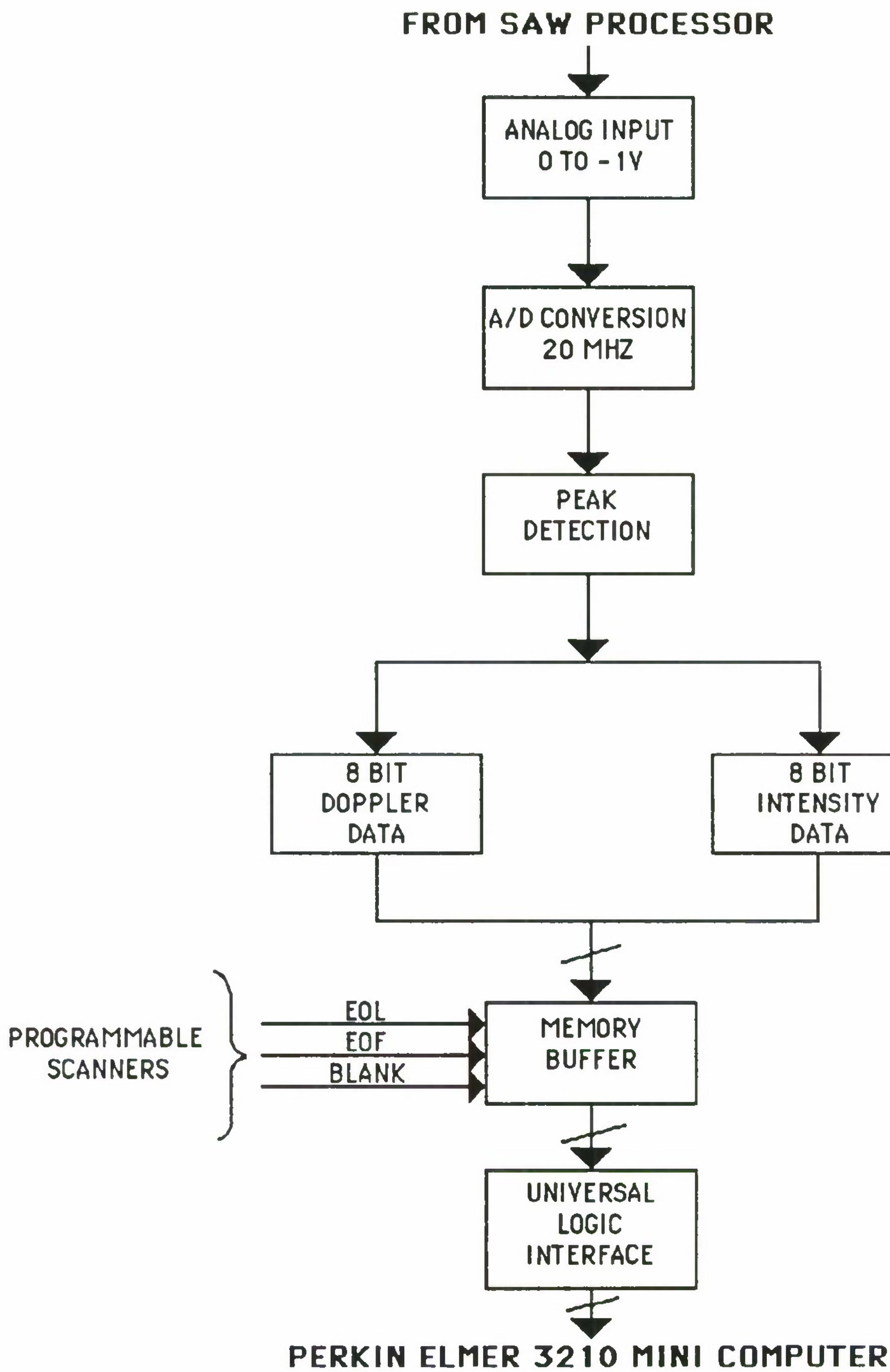

FIGURE 7. BLOCK DIAGRAM FOR THE 20MHz DOPPLER DIGITIZER PROVIDING 8 BITS OF DOPPLER INTENSITY, AND 8 BITS OF FREQUENCY RESOLUTION.

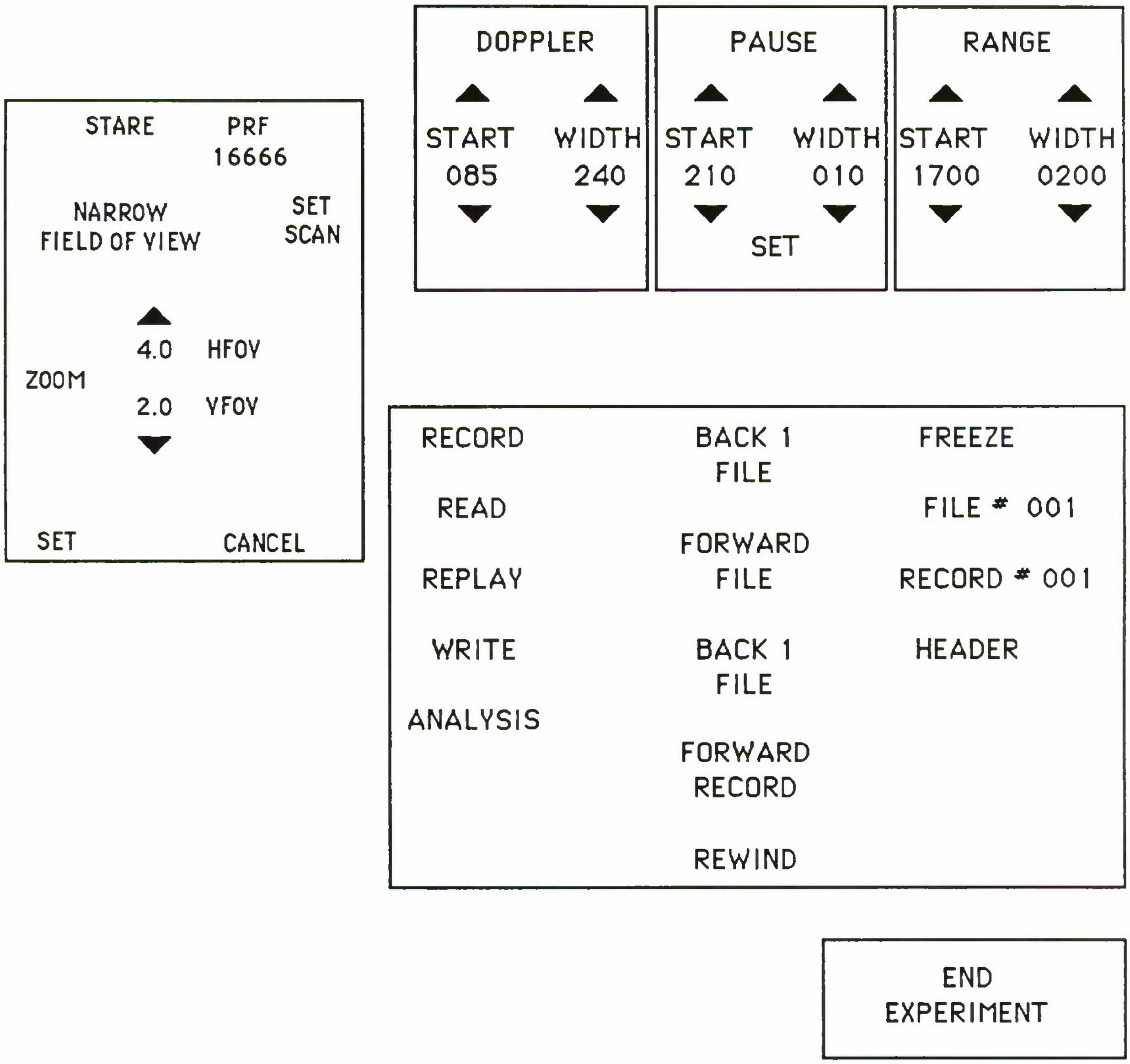

FIGURE 8. A REPRESENTATION OF THE SYSTEM FUNCTIONS AVAILABLE THROUGH THE TOUCH SCREEN MENUS.

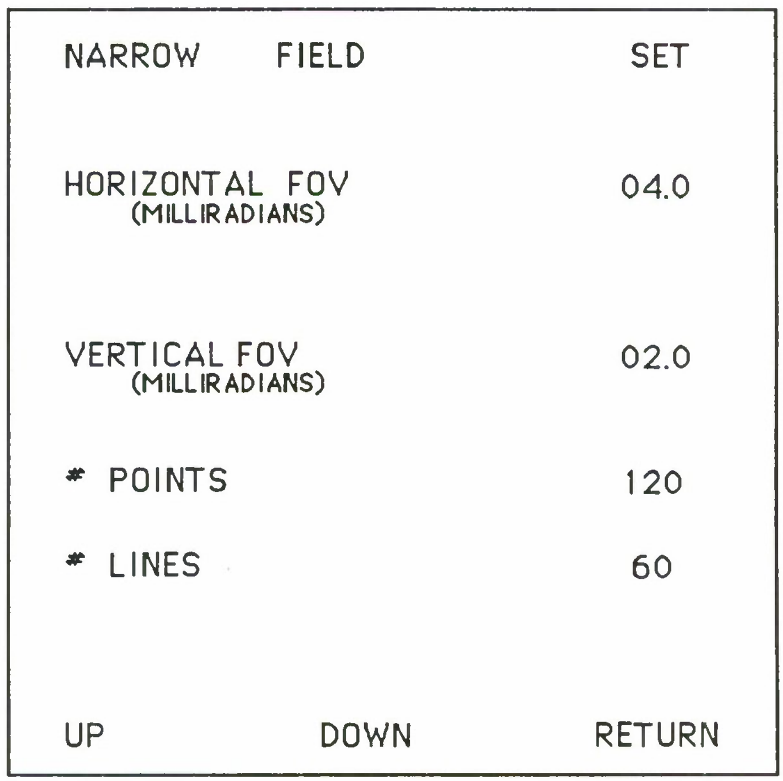

FIGURE 9. A REPRESENTATION OF THE SYSTEM SUB-TOUCH SCREEN CALLED UP THROUGH THE SET SCAN FUNCTION.

2.8 Programmable Scanners

The horizontal scanner is a General Scanner model G120PDT, and the vertical scanner is a General Scanner model G350TTX. The scanner control circuitry is self contained as shown schematically in Figure 10. The scanners were calibrated upon initial installation. Scanner control signals are communicated via RS232 protocol. The control includes scanner amplitude (Field of View) and scan rate (number of pixels). Fly-back and dead time have been taken into account in making the scan drive signal.

3.0 SOFTWARE DESCRIPTION

In this section we discuss the operation of the Perkin Elmer 3210 minicomputer as the system controller. The 3210 is a 32 bit minicomputer that incorporates a dual bus structure, a MUX bus for device control, and a direct memory address bus (EDMA or DMA)for interface to the graphics terminal (data display) and real time data throughput. The system software is written in FORTRAN and Assembler language.

Figure 11 is a block diagram of the overall software controller. Three processes run concurrently and are identified by the double walled boxes. These processes handle data flow from the three digitizers, and touchscreen/keyboard interrupts. The following sections provide detail on these functions.

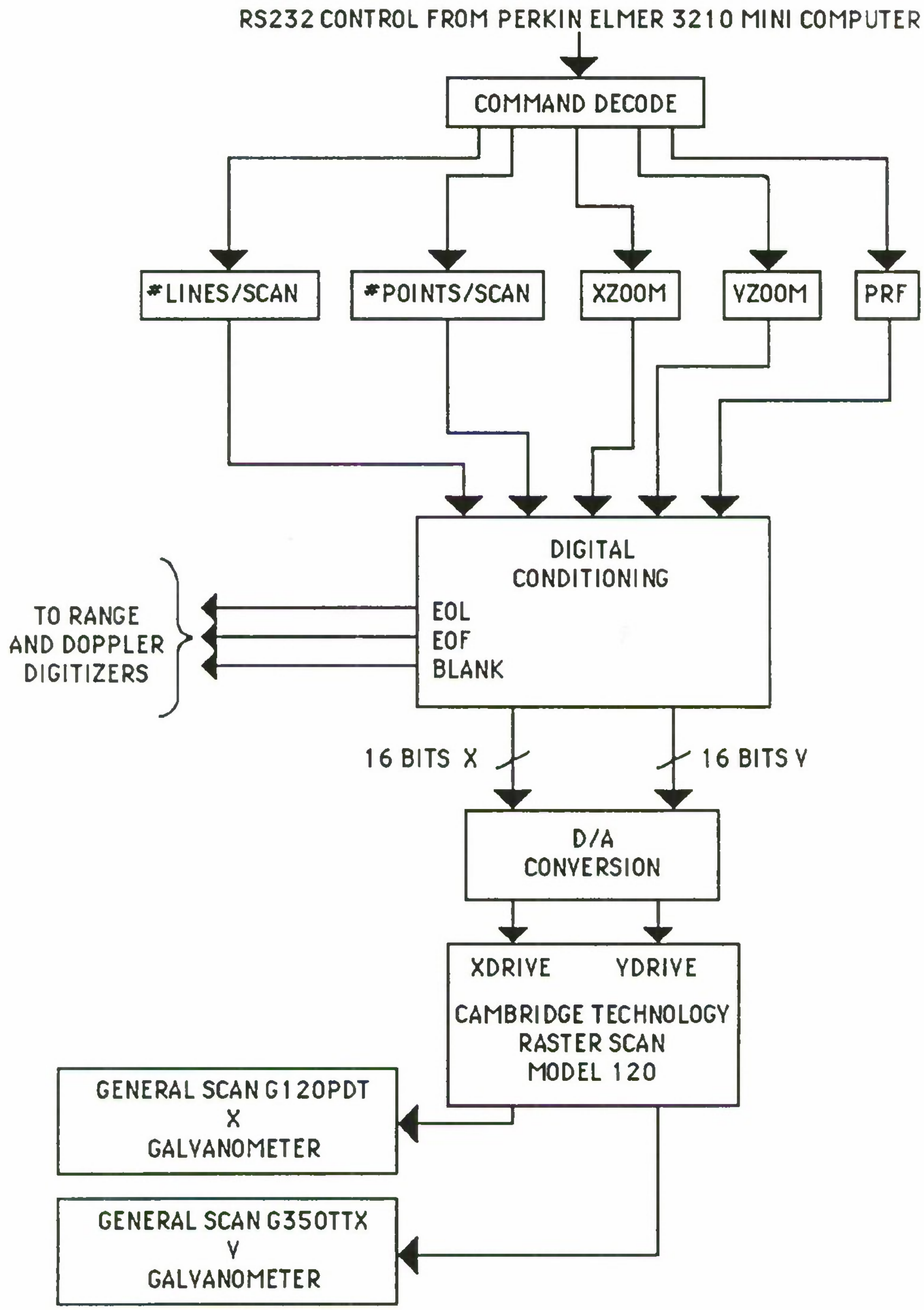

FIGURE 10. BLOCK DIAGRAM OF THE SCANNER CONTROL BOX. SCANNER CONTROLS ARE SENT VIA RS232 FROM THE PERKIN ELMER COMPUTER.

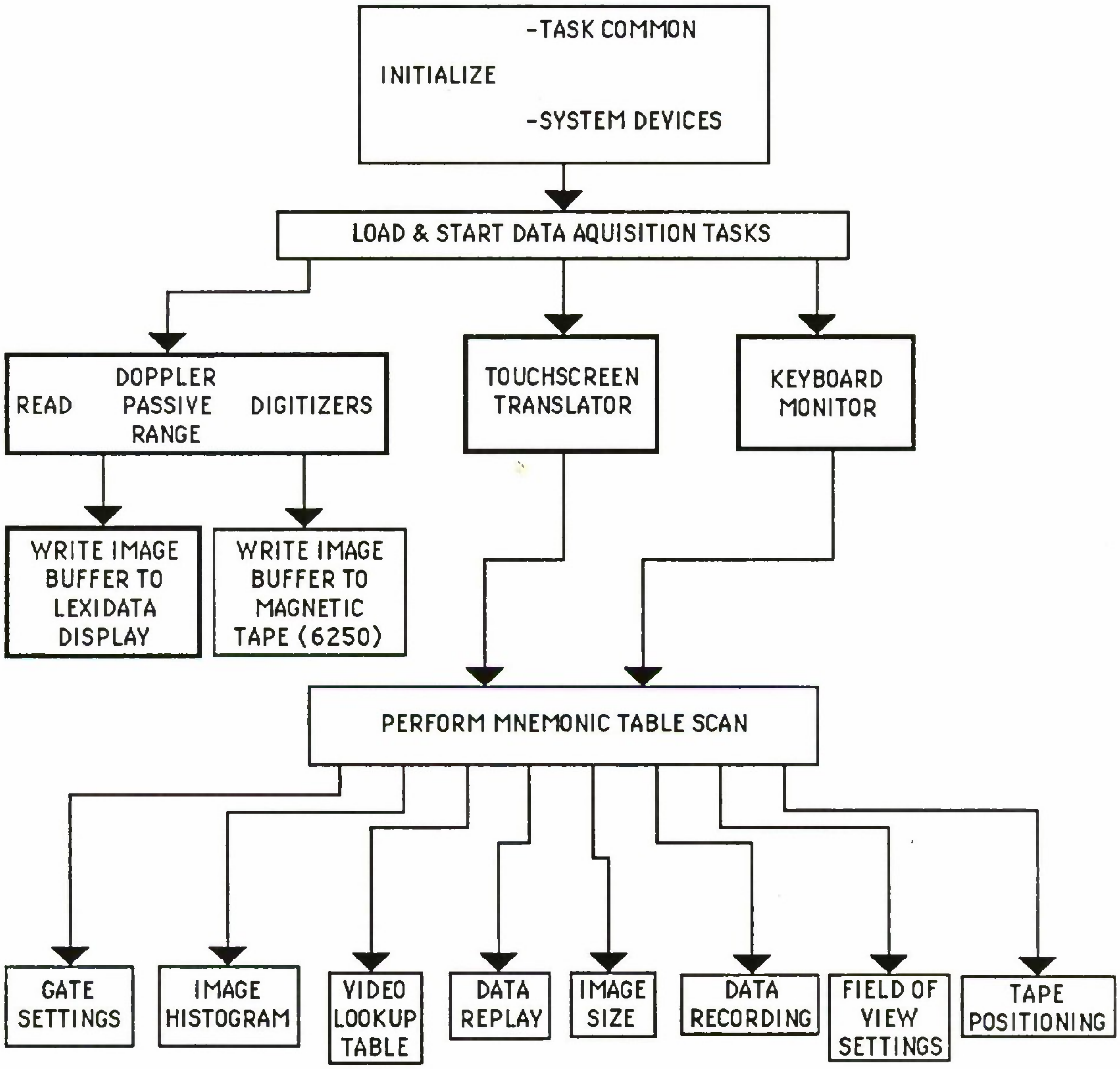

FIGURE 11. OVERVIEW OF THE SYSTEM RESIDENT AND CALLABLE SOFTWARE CONTROL PROCEDURES.

3.1 System Initialization

System initialization consists of two steps (block 1), memory management setup (task common block initialization) and device initialization (setting system clock, range gates, scanners, touchscreen, FOV, and the IEEE devices). The second step (block 2) involves the loading and starting of the three concurrent management routines (block 3).

Task common is a large common block that essentially consists of two image buffers. An "image" in this sense is the total pixel data from all the digitizers for a full radar image. One task common image buffer is read into from the digitizers while the other is read out to the display and tape drive (if on). At the end of the frame the buffers are flip-flopped and the process repeated.

On initialization the common block is zeroed, and the three resident control processes are initialized and started.

3.2 Concurrent Processing

The three resident processes (blocks 3) are the DMA data flow manager which controls data flow from the digitizers to the display and recording devices; the touchscreen control process which issues appropriate interrupts for system controls; and the keyboard monitor process.

System functions are set through the touchscreen or the system keyboard. Figures 8-9 are a representation of the touchscreens, Figure 9 is a subscreen called up by the scan set function. The various touchscreen functions are also accessible through the keyboard monitor. When the touchscreen is addressed a flag is set in the mnemonic block which acts as an interrupt that starts the appropriate job. In addition to the functions called out through the touchscreen there are also data histogram and VLT (look-up table) routines available from the keyboard.

3.3 Interrupt Handling

When an image buffer is completely filled by a digitizer, the DMA data flow manager sends a message interrupt to the data display and tape writing tasks. Reception of the message interrupt causes these tasks to write the filled buffer to the appropriate devices. Meanwhile a second buffer is used for the storing of digitized data preventing loss of data during the tape writes and screen updates.

The touchscreen and keyboard communication tasks are always enabled. Upon receiving input they pass the command to a mnemonic parsing task which loads and starts the appropriate tasks.

4.0 CONCLUSION

This report includes a description of a large aperture multi-dimensional laser radar. The radar has 33μrad resolution at 10.6μm and provides simultaneous range, velocity, intensity, and passive (3-5μm) pixel registered images. Scanners are fully programmable in a raster scan pattern with a pixel rate of up to 20 kHz. Image data is displayed and recorded in real time.

This sensor has been used to collect a variety of data. In particular the data base includes Doppler, range, and passive images of a variety of helicopters out to 7 km, and some ground vehicles at 1 km and 2.6 km. Figure 12 is an example of sensor output. The image consists of Doppler (two people walking next to a moving car), Doppler intensity, range (foreground wires are range gated out), range intensity, 3-5μm passive, and BW video.

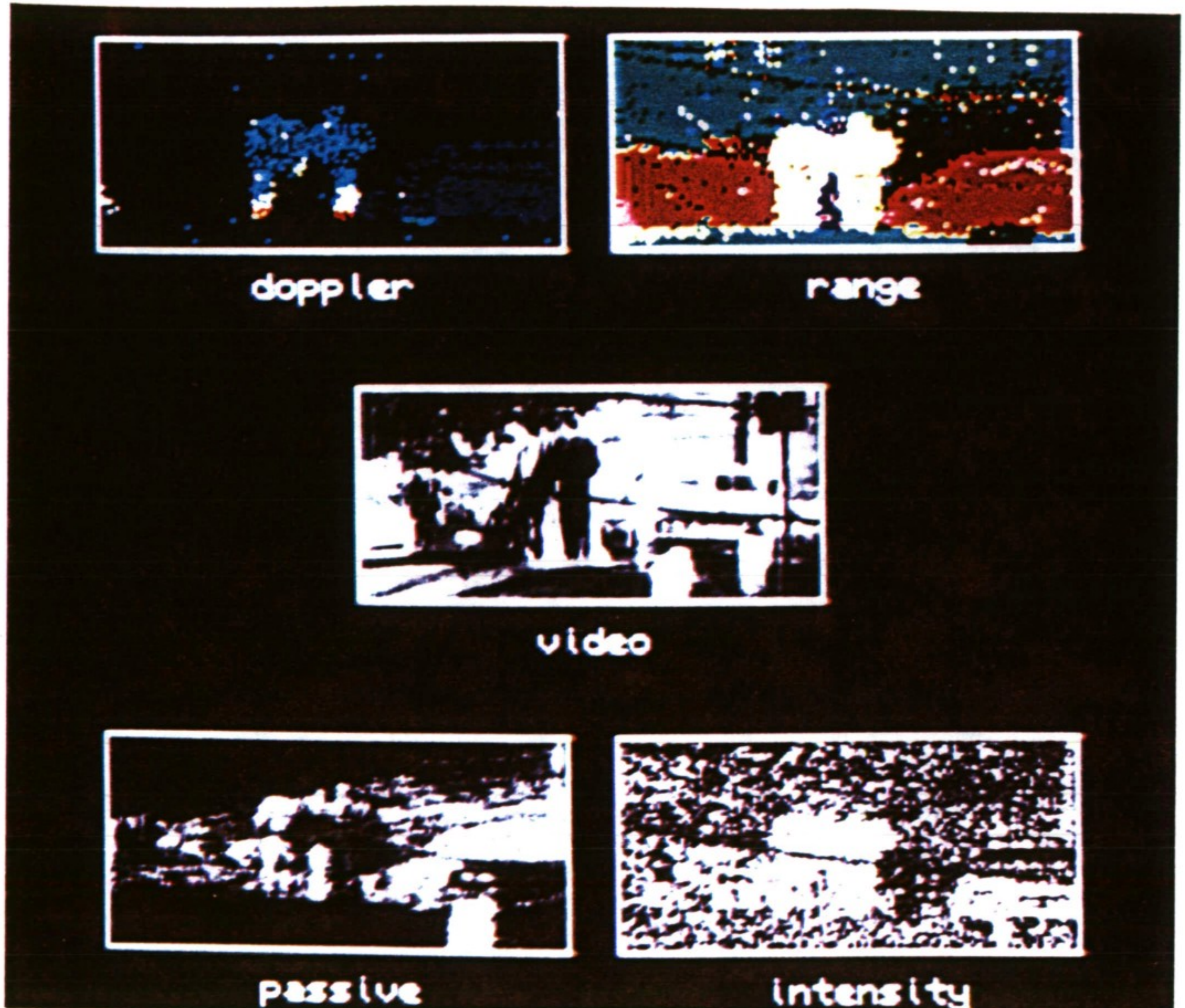

FIGURE 12. EXAMPLE OF SENSOR IMAGERY.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of Brian Edwards and David Ireland in the construction and alignment of the sensor. We also thank Louis Hirshberg for his contributions in assembling much of the electronics.

BIBLIOGRAPHY

1. D.R. Arsenault and V.S. Dolat, 'Compact Multiple-Channel SAW Sliding-Window Spectrum Analyzer,' IEEE Ultrasonic Symposium 1981.

2. U.S. Patent number 4690551.

APPENDIX

System Procedures
System On

Procedures to bring the Perkin Elmer 3210 up
Switch power on (in back) bottom
Switch power on (in back) top
Turn computer key to "ON" from "Standby"
Insert user disc
Push Start/Stop button on the user Disk Drive
Wait for Green light to stop flashing (on drive)
Push Enable/Disable to "Enable" position
Push Init button then release
Return Enable/Disable to "Disable"
Turn computer key to "Lock" from "On"

Commands to be entered from the keyboard

```
DEVICE=d19f                 *BOOTING FROM FIXED DISK
      =os32tst5.os          *USE OPERATING SYSTEM
*ENTER DATE AND TIME
*set  time mm/dd/yy,hh:mm
*ma lrk1:,on,,cd=all        *READIES FIXED DISK
*sysup                      *READIES REMOVEABLE DISK & MTM
```

Data Acquisition

```
*v user                     *USE REMOVEABLE DISK
*loadall                    *LOADS DATA MANAGEMENT PROGRAMS
```

System Down

Procedure to bring the Perkin Elmer 3210 down

```
*v mt7a                     *ACCESS THE SYSTEM DISK
*.spl term                  *DISABLES THE PRINTER
*sysdown                    *DISABLES MTM
                            *MARKS USER DISK OFF
*ma lrk1:,off               *MARKS SYSTEM DISK OFF
```

Turn computer key to standby
Push green light on removable user disk drive
When green light goes off completely remove disk
Switch memory off in back (top)
Switch power off in back (bottom)

Program Options

To enter a command from the terminal one muse type "key" at the system prompt. The system responds with

```
     KEYBOARD>options        *ENTER OPTIONS
OPTIONS                      *displays a list of options
GATES                        *set Doppler and pause gates
RANGE                        *set range gate
VLT                          *change the data display VLT
SIZE                         *change scanner pixel settings
FOVTERM                      *change FOV (narrow or wide)
SETTING                      *change scanner amplitude settings
DEAD                         *change scanner dead time
PRF                          *change system clock
EOE                          *end of experiment
```

System Failure With Disks Marked On

Steps taken in the event of failure with disks marked on

```
Turn computer key to "ON"
Push Enable/Disable to "ENABLE"
Push INIT button the release
Push Enable/Disable to "DISABLE"
turn computer key to "LOCK"
DEVICE=d19f                  *BOOTING FORM FIXED DISK--USE CAPS
       =os32tst5.os          *SELECT OPERATING SYSTEM
*ENTER DATA AND TIME
*set time ,,ddyy,hh:mm
*ma lrk1:,on,p               *MARK LRK1: ON PROTECTED
*lo  f,fastchek              *LOAD SYSTEM CHECKING PROGRAM
*opt res
*ma lrk1:,off
*t f
*st
F>ch lrk1:                   *CHECK SYSTEM DISK FOR PROBLEMS
F> <cr>
F> <cr>
```

```
F> <cr>
F> <cr>
F> <cr>
F> @
F> yes
* F END OF TASK CODE 0
REPEAT PROCESS OF LRK2:
*t f
*st
F>ch lrk1:                 *CHECK USER DISK FOR PROBLEMS
F> <cr>
F> <cr>
F> <cr>
F> <cr>
F> <cr>
F> @
F> yes
* F END OF TASK CODE 0
*t f                       *CANCEL FASTCHEK TASK
*opt non
*cancel f
*ma lrk1:,on,,cd=all       *RING  THE SYSTEM UP
*sysup
```

Note: If the system fails one may first try to perform a system down (marking disks off) followed by a system up. If this is no possible follow the above steps.

Screen Hangup

Steps take when the touchscreen will not respond.

1. Terminate experiment . . . *key <cr>
   KEYBOARD>eoe

2. Bring the Perkin Elmer down
   *v mt7a
   *sysdown
   *ma lrk1:,off

Turn computer key to "ON" from "LOCK"
Push enable/disable key to "ENABLE"
Push the init key then release
Return enable/disable key to "DISABLE"
Perform the system up procedures

Data Display Lexidata Crash

Steps taken when the Lexidata display device crashes.

1. Terminate display program	*cancel receive
2. Re-initialize the Lexidata	*lo lexinit/2 *as 7,lex1: *st
WAIT FOR COMPLETION	
3. Restart display program	*t receive *st
4. Reset the display VLT	*key KEYBOARD>vlt BWVLT>0 255

REPORT DOCUMENTATION PAGE

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None

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	laser radar; range measurements; SAW spectrum analyzer; Doppler measurements; passive detectors

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A 39 cm aperture multi-dimensional laser radar has been built and made operational. This sensor acquires pixel registered range, Doppler, 3-5 μm passive, and visible passive data. Range is digitized at 200 MHz for .75 m range resolution, Doppler is resolved to .5 mph with a SAW spectrum analyzer. Multi-dimensional images can be taken with an angular resolution of from 33 μrad to 1 mrad. Image size and data flow are controlled by a minicomputer. The technical details of this laser radar testbed are the subject of this report.

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